NISTIR 5850 R

Rubber Particles from Recycled Tires in Cementitious Composite Materials

Hai Huynh*
Dharmaraj Raghavan*
Chiara F. Ferraris

May 1996
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

* Department of Chemistry, Howard University, Washington DC 20059

National Institute of Standards and Technology
Michael Kantor, *Secretary*
Technology Administration
Mary L. Good, *Under Secretary for Technology*
National Institute of Standards and Technology
Arati Prabhakar, *Director*

Abstract

A possible method for recycling used automobile and truck tires could be to comminute them and incorporate the rubber particles into concrete. In a preliminary investigation, mechanical properties of mortar containing ground or shredded tires were evaluated. In this study, two different shapes of rubber particles were used as constituents of mortar : granules of about 2 mm diameter and shreds having two sizes which were, nominally, 5.5 mm x 1.2 mm and 10.8 mm x 1.8 mm (length x diameter). It was found that addition of rubber granules led to a decrease in both compressive and flexural strengths of mortar. On the other hand, the addition of rubber shreds improved some of the properties of the mortar. In particular, the crack width and crack length due to plastic shrinkage were reduced for mortar containing the 10.8 x 1.8 mm rubber shreds compared with a control mortar without rubber particles. The mortar containing rubber shreds showed workability comparable to that of a mortar without rubber particles. A mortar containing 25.4 mm long and 15 μm diameter polypropylene fibers showed poor workability compared with a mortar containing rubber fibers.

Although further studies are necessary, it appears that the incorporation of shredded rubber could be beneficial for reducing plastic shrinkage crack development of mortar and probably concrete.

Keywords: Building Technology; Rubber-concrete; Rubberized mortar; Plastic Shrinkage; fibrous rubber; Strength; recycled rubber tires

Table of Contents

List of Figures

List of Tables

1. INTRODUCTION

The United States produces about 279 million scrap tires per year (1). The practice of disposing scrap tires in landfills is becoming difficult because of the rapid depletion of available sites for waste disposal. Proposed alternatives include recycling the tires as fuel for cement kilns, as feedstock for producing carbon black, as reefs in marine environments, and in asphalt as paving material (2-4). Using tires as fuel is technically feasible but not economically attractive because of the high initial capital investment (4,5). On the other hand, the use of tires in asphalt is technically feasible and can be economically attractive. However, the asphalt industry can currently absorb only 30 % to 40 % of the scrap tires generated (6). Another alternative that has been suggested is to mix rubber particles from scrap tires into portland cement concrete. Possible uses of the concrete would be in subbases for highway pavements, highway medians, sound barriers and other transportation structures (7). Until now, most of the research on uses of rubber particles in concrete has been conducted using granular rubber (8-14). Particle sizes used have ranged from 0.06 mm to 2 mm in diameter. The results have shown that the compressive and flexural strengths of concrete decreased on addition of granular rubber. Nevertheless, other properties are reported to have been improved, for example, freeze-thaw resistance and impact resistance (7).

In the present study, the influence of the shape of rubber particles on mechanical properties of mortar was examined by using rubber granules of about 2 mm in diameter (GR 2) and two sizes of fibrous rubber (one being about 5.5 mm long and about 1.2 mm diameter, and the other being about 10.8 mm long and about 1.8 mm in diameter). The rationale for using fiber-shaped rubber particles is that the addition of fibers (steel, glass, carbon, polypropylene) to concrete has resulted in concrete which is less prone to brittle failure and to plastic shrinkage cracking (15-17). For convenience, in this exploratory study, mortar was used instead of concrete in the belief that the effects on mortar and concrete would be similar.

As expected, this study confirmed the findings of previous work that granular rubber decreases compressive and flexural strengths. An encouraging discovery was that plastic shrinkage cracking can be reduced by the addition of sufficient fibrous rubber. Further investigations are required to verify that similar benefits can be obtained by adding rubber to concrete.

2. EXPERIMENTAL PROCEDURE

2.1. Materials and specimen preparation

The characteristics and proportions of the materials used are summarized in Table 1. The process employed for comminution often dictates the particle shape and the amount of rubber present with a particular particle shape. Mechanically ground tire rubber was used in the investigation. Representative dimensions of rubber particles were determined by measurements under a light microscope. Table 2 summarizes the lengths and diameters of the two sizes of rubber fibers. The reported values are the average of 20 measurements on different particles. The fibrous rubber was received in bulk and separated into two size fractions by sieving using standard sieves (ASTM E11) (20).

Rubber fibers that passed through the 4.75 mm sieve (#6) and were retained by the 2.36 mm sieve (#8) were designated as FR 4.75, while the rubber fibers that passed through the 2.36 mm sieve (#8) and were retained by the 1.18 mm sieve (#16) were designated as FR 2.36. This rudimentary method of separation into two sizes was deemed adequate for an exploratory study. GR 2 represents granular rubber of approximately 2 mm diameter. Figure 1 shows the different rubber particles and polypropylene fibers used for comparison in the study.

Mortar batches were prepared as described in ASTM C 109 (18). The same ratios of sand, cement and water were used in all batches. The rubber was added at the end of the standard mixing cycle, and the mortar was mixed for an additional 2 minutes. The specimens for strength measurements the specimens were, after molding, covered with wet paper towels and cured in a chamber at 100% RH and room temperature (23 $\pm$ 2°C) for 24 hours. After demolding, the specimens were cured in lime water for 7 days before compressive and flexural strength testing. For the plastic shrinkage cracking tests, the specimens were placed immediately after molding in a drying chamber (section 2.2.2) for at least 3 hours.

Table 1: Materials and mixture proportions

Material	Type/Source	Ratio by mass of cement
Cement Sand Water	ASTM portland cement Type I-II US Silica, Ottawa USA Graded sand ASTM C 778 Distilled water	1 2.75 0.485
Rubber Granules (2mm diameter) Fibers	 Baker Industries, Indiana Rouse Rubber, Mississippi (see Table 2)	 0, 1, 2.5, 5, 10, 15 % 0, 1, 2.5, 5, 10, 15 %
Polypropylene fibers	W.R. Grace & Co. 25.4 mm long, 15μm diameter	1 %

Table 2: Dimensions of fibrous rubber

Type of rubber particles	Average diameter* (mm)	Average length* (mm)	Average aspect ratio
FR 2.36	1.2 ± 0.6	5.5 ± 2.2	4.6
FR 4.75	1.8 ± 0.8	10.8 ± 4.5	6.0
Notes: * Measurements of 20 fibers ± means standard deviation			

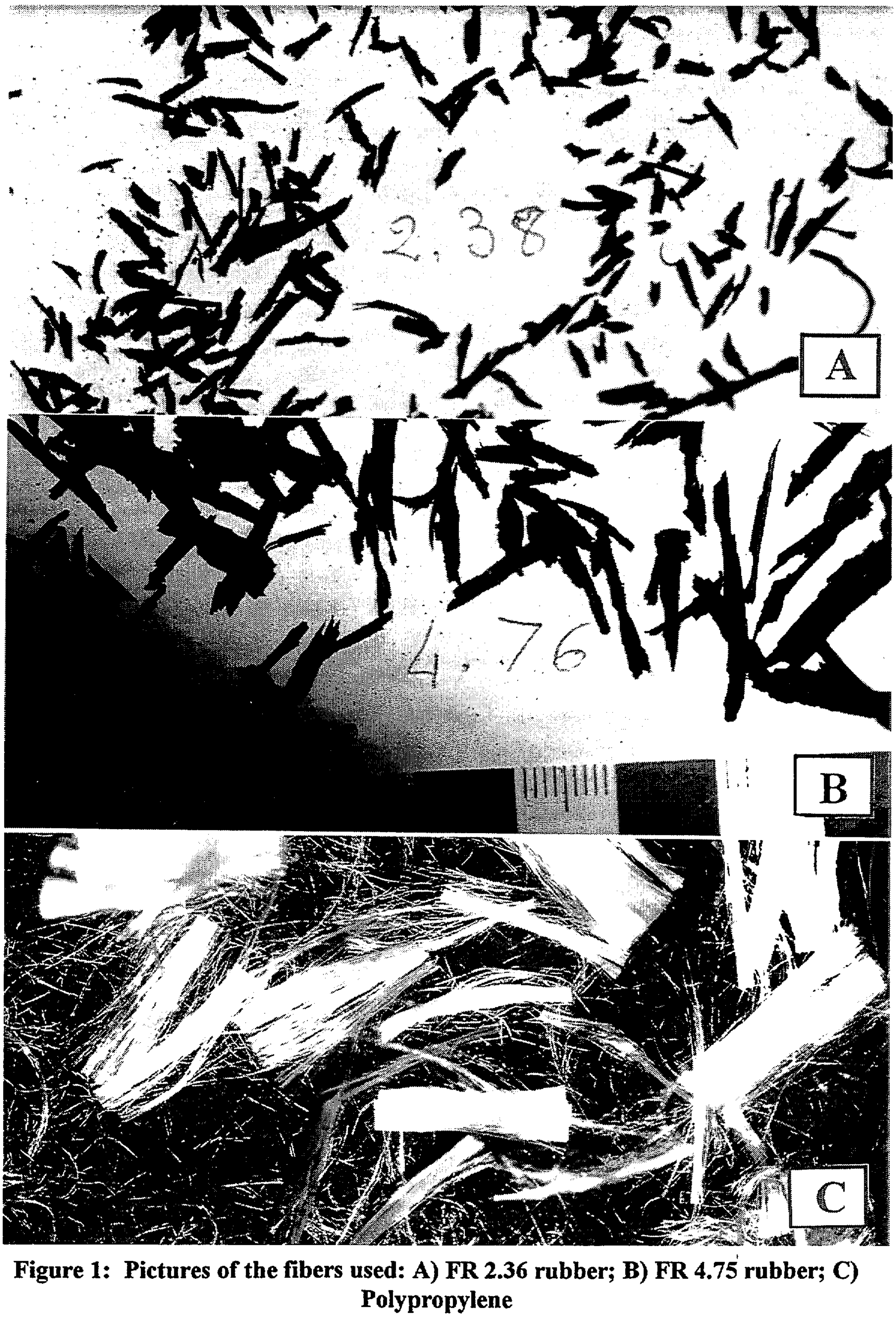

Figure 1: Pictures of the fibers used: A) FR 2.36 rubber; B) FR 4.75 rubber; C) Polypropylene

2.2. *Test Methods*

2.2.1. Compressive and flexural strengths

The specimens for compressive strength measurement were 50 mm (2 in.) cubes and 75 mm diameter x 150 mm long (3 in. x 6 in.) cylinders. The specimens for flexural strength measurements were 25 mm x 25 mm x 279 mm (1 in. x 1 in. x 11 in.) beams. For each mixture, the batches included nine cubes, and seven beams. The cylinders batches were composed of five cylinders. The compressive strength was determined according to ASTM C 109 (18) for the cubes and ASTM C 39 (21) for the cylinders. The tests were performed in a 266 kN Baldwin universal testing machine[1]. The cylindrical samples were capped by unbonded neoprene caps. The flexural strength of the beams was measured using one-third point loading as described in ASTM C 78 (22). The tests were performed on a 810 Materials Testing System[1] (MTS) machine.

2.2.2. Plastic shrinkage cracking

The resistance to plastic shrinkage cracking was determined on control mortar, mortar with polypropylene fibers, and mortar with fibrous rubber. The content of rubber ranged from 1 % to 15 % of cement by mass, while the content of polypropylene fibers was 1 % of cement by mass. The specimens used to study plastic shrinkage cracking were cast in 550 mm x 250 mm x 45 mm molds. A sketch of the mold is shown in Figure 2. The mold dimensions were one-half of those described in the draft protocol currently under review by the ASTM subcommittee on fiber reinforced concrete (17). The molds include sheet metal triangular inserts to anchor the ends of the specimens and provide for stress concentration at the center of the specimen. A laboratory hood was used as a drying chamber. Immediately after molding, the slabs were placed in the hood for 3 hours. Figure 3 shows the placement of the plastic shrinkage molds within the hood. A heater and fan were used to control the evaporation rate within the chamber. Four beakers containing a known amount of water were placed as shown on Figure 3. The evaporation rate was determined by the loss of water mass during the three hours of the drying test. The temperature and the air flow rate of the chamber were adjusted to attain an evaporation rate range of approximately 1150 to 1180 $g/m^2/h$, in order to produce severe conditions that would induce cracking in the control mortar. The time of crack formation and crack growth were monitored for the initial 3 hours. The crack length was determined by placing a string along the crack and then measuring the string length, while the crack width was measured using a crack width comparator[2]. The crack length reported represents the sum of the lengths of the cracks detected in the specimen. The crack width is the average of three measurements for each specimen.

---

[1] Certain manufacturers names and names of instruments and materials are identified in this paper to adequately describe the experimental procedure. Such an identification does not imply recommendation or endorsement by the National Institute of Standards and Technology and Howard University, nor does it imply that instruments or materials identified are necessarily the best available for the purpose.

[2]CTL, crack width compactor, 1988

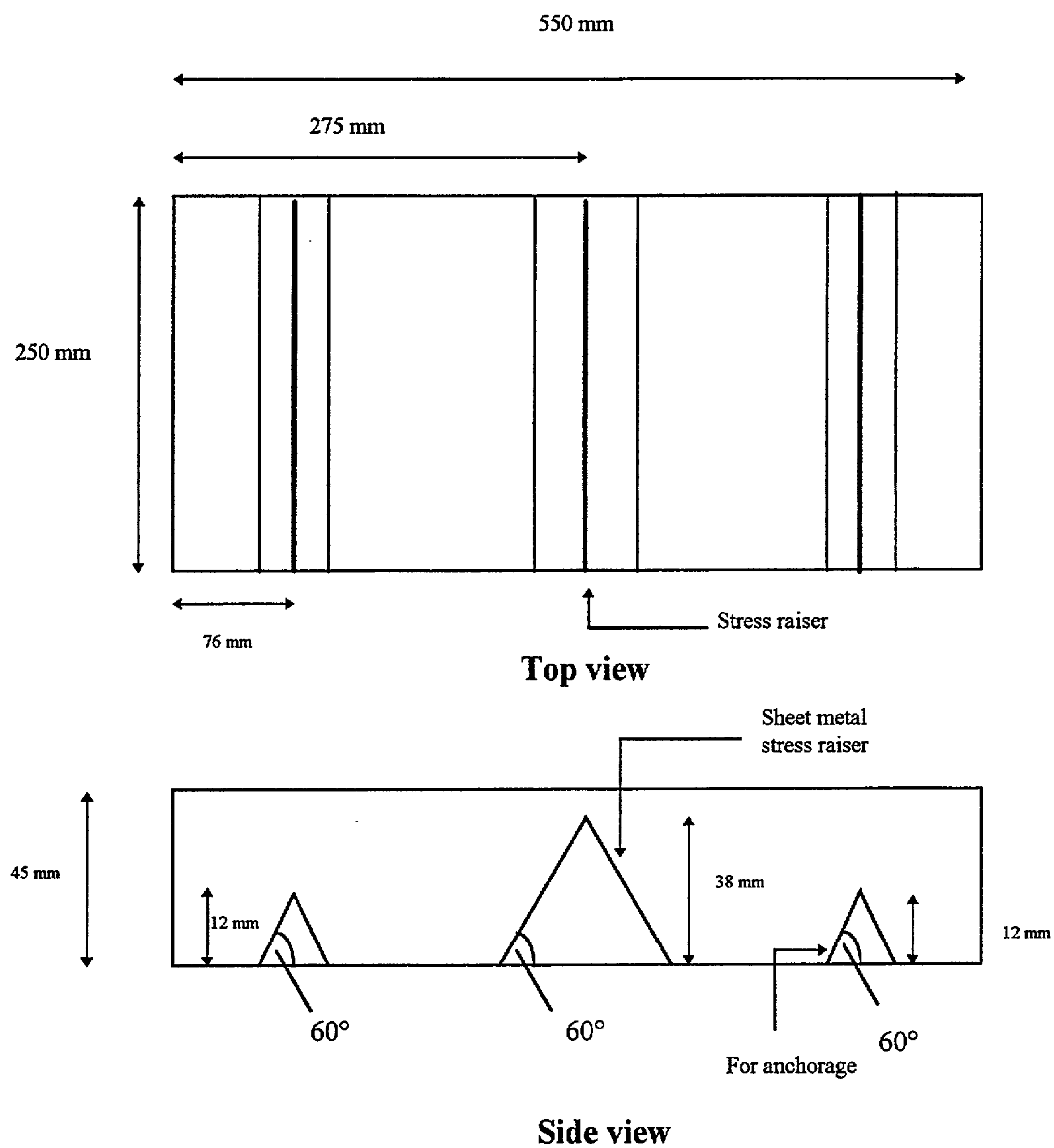

Figure 2: Schematic of mold used for determination of plastic shrinkage cracking.

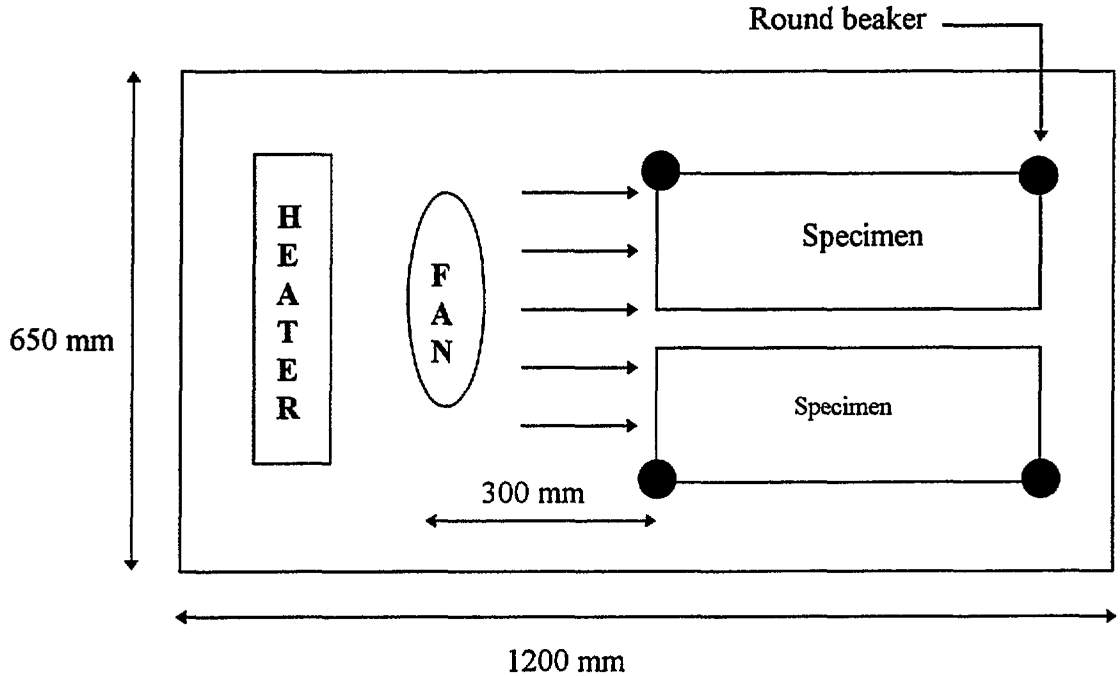

Figure 3: Schematic of the mold placement in the drying chamber for plastic shrinkage cracking measurements.

2.2.3. Workability

The workability of the mortar was measured using a VeBe test (24). A sketch of the VeBe apparatus is shown in Figure 4. The apparatus is intended to be used for mixtures where specimens are compacted by vibration. The workability was determined on control mortar, mortar with polypropylene fibers, and mortar with rubber fibers. The content of rubber fibers was 1 to 15 % of cement by mass, while the content of polypropylene fibers was 1 %. A slump cone was filled with the mortar mixture. The cone was removed and a circular plate, whose diameter was slightly less than that of the cylindrical container, was placed on the top of the specimen. The vibrating table was turned on and the initial time was recorded. During the test, care was taken to guide the circular plate through the container. When the bottom of the transparent circular plate was completely covered with mortar, the vibrating table was turned off and the time was recorded. The time difference, the VeBe time, is a measure of the workability of the mixture. A shorter VeBe time represents a more workable mixture. The reported results are averages of two or three tests.

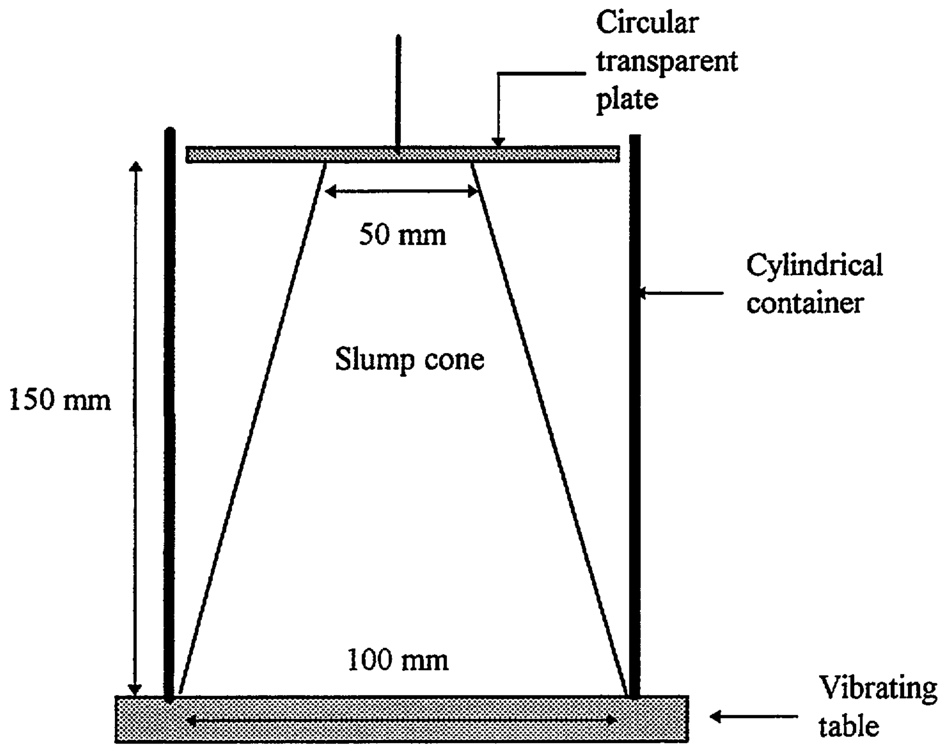

Figure 4: VeBe apparatus used for workability measurements.

3. RESULTS AND DISCUSSION

3.1. Compressive Strength

Figure 5 shows the individual compressive strengths of cube specimens for the different batches. Mixtures with more than one batch are indicated by the boxes surrounding the points. The within-batch coefficient of variation ranged from 2% to 9%. Figure 5 shows that increasing the content of rubber decreased the compressive strength of mortar. At 1, 2.5, and 5 % rubber by mass of cement, fibrous rubber showed a smaller reduction in compressive strength of mortar than granular rubber. However, the trend did not hold true with the addition of 10% rubber by mass of cement. To examine whether there were statistically significant differences in the average compressive strength due to the type of rubber or combination of amount of rubber and type of rubber, an analysis of variance (ANOVA) and a post-hoc (Scheffé method) test was used. A software package was used to determine the confidence level (probability) at which the mean compressive strengths of mortar containing granular rubber and fibrous rubber were different. Any confidence level below 95% was equivalent to no statistically significant difference. Table 3 summarizes the difference in cube strength due to rubber type for different amounts of rubber. Table 3 shows that the addition of 1% fibrous rubber did not significantly affect the compressive strength of mortar, but the addition of 1% granular rubber caused a significant reduction in the compressive strength.

There was a significant difference in the mean compressive strengths of mortar containing 1% granular rubber and 1% fibrous rubber. A similar effect was noticed for the mortar containing 5% rubber. However, the trend did not hold true with the addition of 10% rubber by mass of cement. Overall, the ANOVA revealed that rubber type did not have a significant effect on the compressive strength of the mortar, but there was a strong interaction effect between rubber type and rubber content. For some rubber content, rubber type had a significant effect on the compressive strength of the mortar.

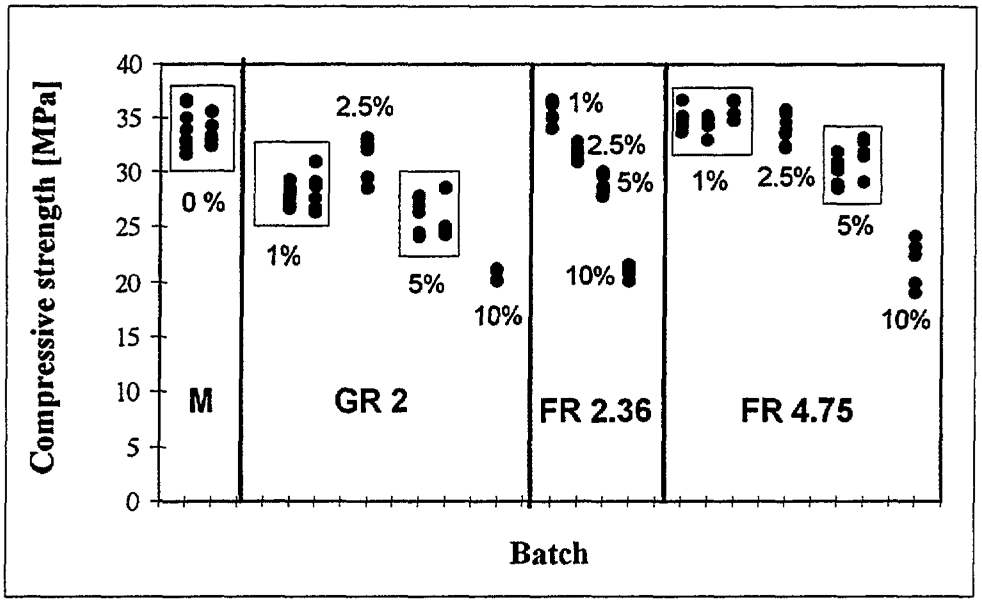

Figure 5: Compressive strength of mortar cubes.

Figure 6 shows the individual compressive strengths of the cylindrical mortar specimens. No replicate batches were included in these tests. The within-batch coefficients of variation ranged from 1.4 to 4.5%. As was the case with cube strength, Figure 6 shows that increasing the content of rubber decreased the cylinder compressive strength of mortar. The plot also indicates that among the three rubber types, FR 4.75 resulted in the smallest reduction in compressive strength of the mortar. The differences due to fiber type were investigated by an ANOVA and a post-hoc (Scheffé method) test was used to determine the confidence level at which the mean cylinder compressive strengths of mortar containing granular rubber and fibrous rubber were different. Table 4 indicates that with the addition of 1 and 10% rubber by mass, the mean compressive strength of mortar containing FR 4.75 was significantly higher than that of mortar containing either granular rubber or FR 2.36. However, for the 1 and 10% rubber content, the mean compressive strengths of mortar with GR 2 and FR 2.36 particles were not significantly different. In summary, the results of the cylinder tests appear to show that the FR 4.75 rubber fibers resulted in better performance than the other particles. However, because there were no replicate batches, this conclusion should be viewed with caution.

Table 3: Differences in mean compressive cube strength for different rubber type and contents

Rubber type and content	Difference in compressive strength [MPa]	Standard error [MPa]	Confidence level ** [%]
N - GR2 (1)	5.6***	0.44	≈100
N - FR2 (1)	-1.50	0.61	*
N - FR4 (1)	-1.19	0.43	*
GR2 (1) - FR4 (1)	-6.80	0.42	≈ 100
GR2 (1) - FR2 (1)	-7.10	0.61	≈ 100
FR4 (1) - FR2 (1)	-0.31	0.59	*
GR2 (2.5) - FR4 (2.5)	-2.71	0.62	99.4
GR2 (2.5) - FR2 (2.5)	-0.39	0.64	*
FR4 (2.5) - FR2 (2.5)	2.32	0.62	96.3
GR2 (5) - FR4 (5)	-4.83	0.46	≈ 100
GR2 (5) - FR2 (5)	-3.09	0.56	≈ 100
FR4 (5) - FR2 (5)	1.74	0.55	*
GR2 (10) - FR4 (10)	-0.63	0.73	*
GR2 (10) - FR2 (10)	-0.15	0.77	*
FR4 (10) - FR2 (10)	0.48	0.69	*

Notes:
N = No rubber
GR2 = Granular rubber 2 mm diameter
FR2 = Fibrous rubber 2.36
FR4 = Fibrous rubber 4.75
Values for rubber percentage are shown in parentheses ( )
* No difference between means
** Confidence level at which the two means are different (Scheffé method)
*** N - GR2 (1) = the difference in the mean compressive strengths of mortar with no rubber and 1% GR2

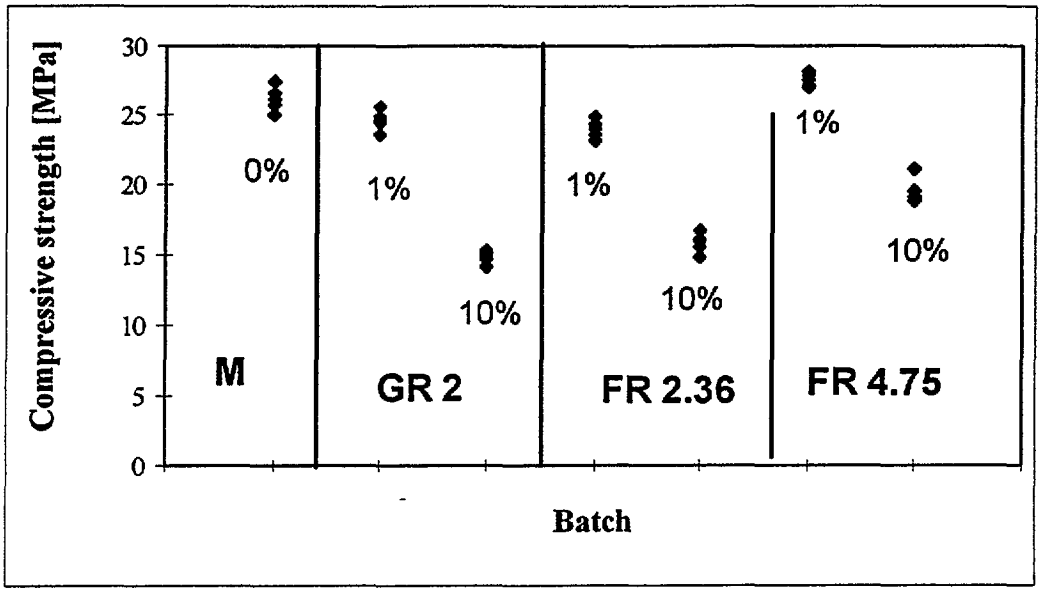

Figure 6: Compressive strength of mortar cylinders.

Table 4: Differences in mean cylinder strength for rubber types and contents

Rubber type and content	Compressive strength difference [MPa]	Standard Error [MPa]	Confidence Level ** [%]
GR2 (1) - FR4 (1)	-2.96***	0.40	≈ 100
GR2 (1) - FR2 (1)	.64	0.42	*
FR4 (1) - FR2 (1)	3.6	0.40	≈ 100
GR2 (10) - FR4 (10)	-4.49	0.44	≈ 100
GR2 (10) - FR2 (10)	-0.97	0.42	*
FR4 (10) - FR2 (10)	3.82	0.44	≈ 100
N-GR2(1)	1.55	0.42	99.7
N-FR2(1)	2.19	0.42	≈ 100
N-FR4(1)	-1.41	0.4	99.5

Notes
N = no rubber
GR2 = Granular rubber 2 mm diameter
FR4 = Fibrous rubber 4.75
FR2 = Fibrous rubber 2.36
Values for rubber percentage are shown in parentheses ( )
* No difference between means
** Confidence level at which the two means are different (Scheffé's method)
*** GR2 (1) - FR4 (1) = the difference in the mean compressive strengths of 1% GR2 and 1% FR4

3.2. *Flexural Strength*

Figure 7 shows the individual flexural strengths of the beams from different batches. The within-batch coefficients of variation varied from 1.4 to 7.6%. Figure 7 shows that increasing the content of rubber decreased the flexural strength of mortar. The results of an ANOVA indicated that overall FR 4.75 showed a smaller reduction in flexural strength of the mortar than GR 2. A post-hoc test (Scheffé Method) was conducted to determine the confidence level at which the mean flexural strengths of mortar containing granular rubber and fibrous rubber were different. Table 5 indicates that with the addition of 1% rubber by mass, the mean flexural strength of mortar containing FR 4.75 and GR 2 were significantly different. However, at 5 and 10% rubber, the differences in the mean flexural strengths of mortar containing FR 4.75 and GR 2 were not statistically significant. In summary, the results of the flexural strength tests appeared to indicate better performance for the FR 4.75 fibers compared with GR 2. However, since there were insufficient replicate batches this conclusion should also be viewed with caution.

The mortar specimens with rubber fibers were able to withstand some load even when they were cracked. This was due to bridging of cracks by the fibers. The specimens did not physically separate into two pieces under flexural loading. Figure 8 shows a fractured mortar specimen containing fibrous rubber. It can be seen that the mortar matrix failed, while the rubber fibers bridged the crack and prevented catastrophic failure of the specimen during the test. Specimens with granular rubber broke in two when the peak load was attained. Therefore, the post-crack strength is improved by switching from granular rubber to fibrous rubber.

Figure 9 is a light micrograph of fractured granular rubber mortar. Microscopic observations of the specimens showed that fracture occurred at the rubber-to-cement interface for the granular rubber inclusion. The pull-out characteristics of the granular rubber particles from the mortar matrix are consistent with poor interfacial bonding. It was not unexpected because similar results have been reported in the literature (8-11).

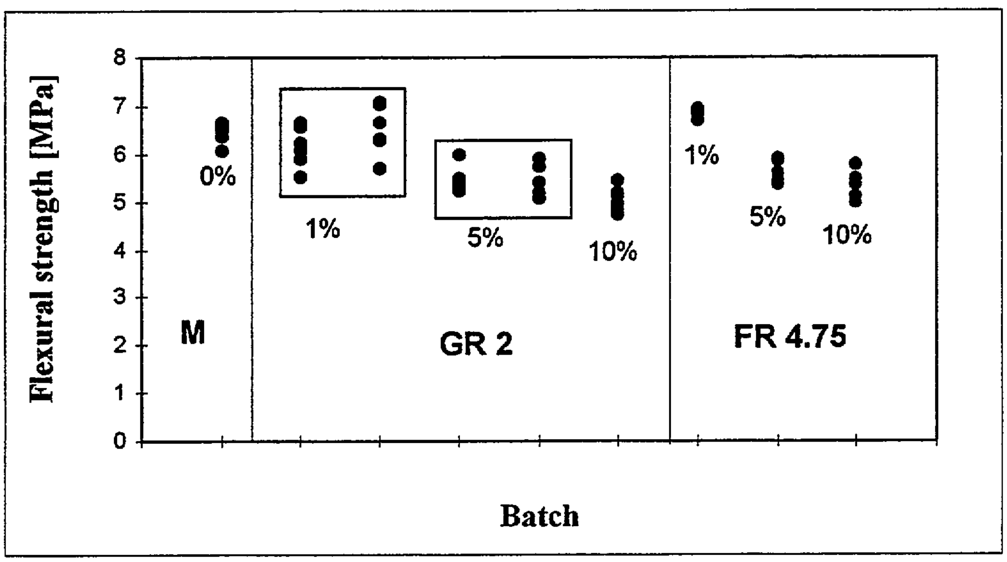

Figure 7: Flexural strengths of mortar beams.

Table 5: Differences in mean flexural strength for rubber type GR2 and FR 4.75

Rubber type and composition	Flexural Strength Difference [MPa]	Standard Error [MPa]	Confidence level** [%]
GR2 (1) - FR4 (1)	-0.52***	0.17	99
GR2 (5) - FR4 (5)	-0.24	0.16	*
GR2 (10) - FR4 (10)	-0.33	0.19	*

Notes:
GR2 = Granular rubber 2 mm diameter
FR4 = Fibrous rubber 4.75
Values for rubber percentage are shown in parentheses ( )
* No significant difference between means
** Confidence level at which the two samples are different (Scheffé's method)
*** GR2 (1) - FR4 (1) = the difference in the mean flexural strengths of 1% GR2 and 1% FR4

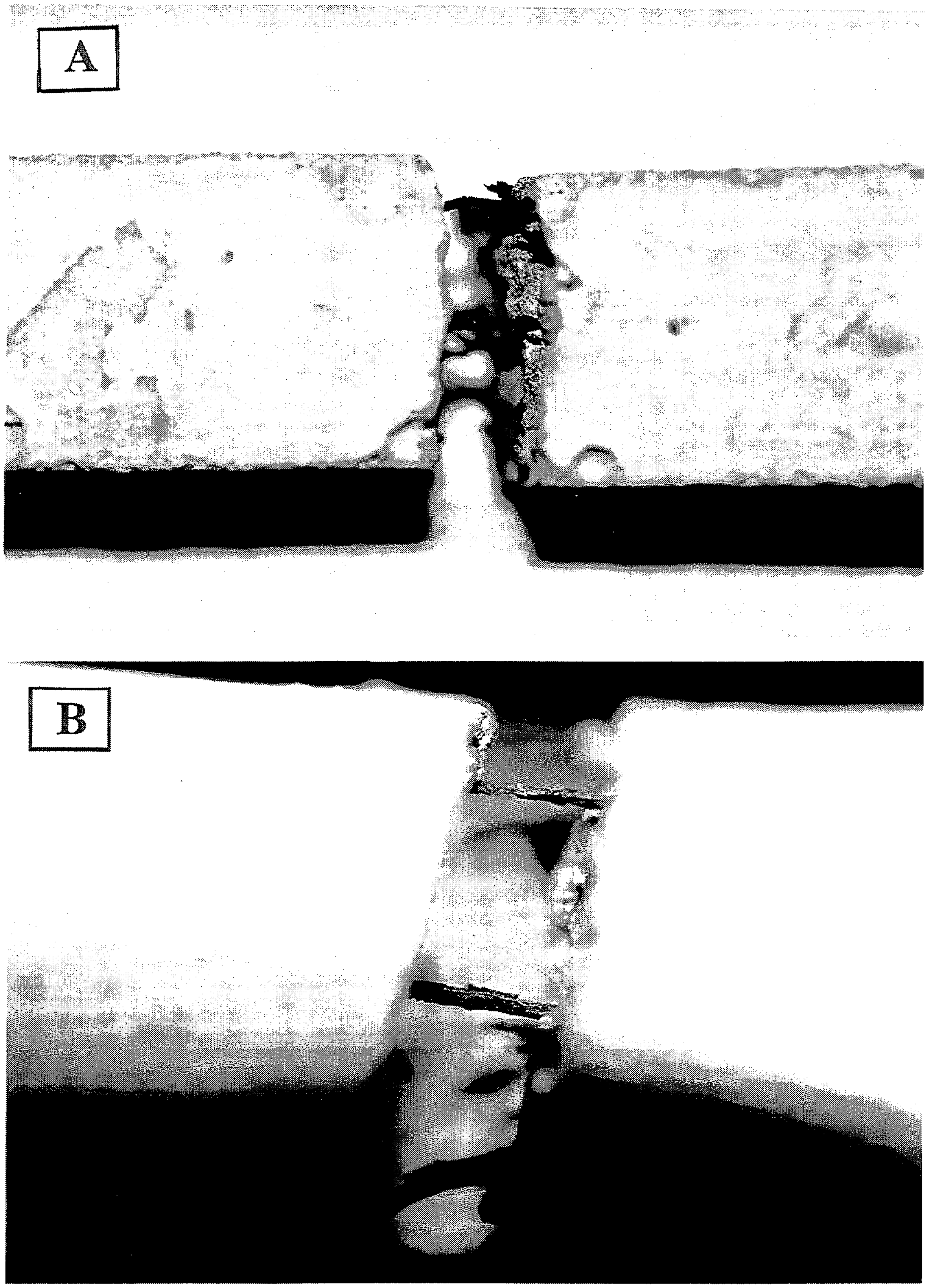

Figure 8: Fractured beam of fibrous rubber mortar. A) As obtained, B) after stretching the two parts (close view of the rubber).

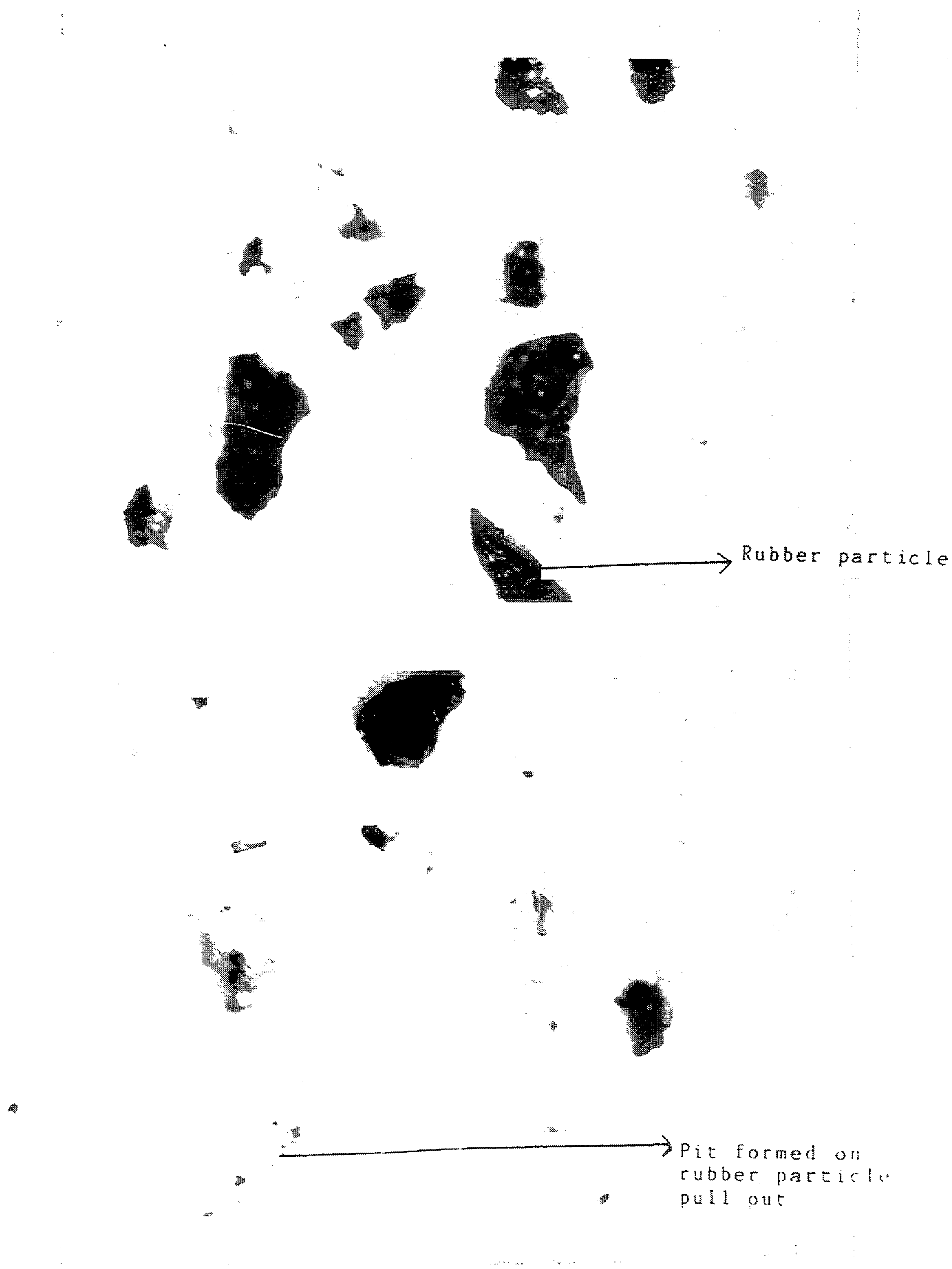

Figure 9: Light micrograph of fractured beam with granular rubber mortar.

3.3. Plastic shrinkage

Figure 10 shows plastic shrinkage specimens with contents of 0, 5, 10, and 15 % of rubber fibers and 1 percent of polypropylene fibers in mortar. The specimens containing 0, 5, 10, and 15 % of rubber fibers cracked, while those containing 1 percent of polypropylene fibers did not crack in the first three hours. In the cracked specimens, the crack was always observed over the central stress raiser. The addition of fibrous rubber, the crack was not continuous. Apparently, crack propagation was arrested several times due to interference by the fibrous rubber. The fibrous particles, despite the weak bonding of rubber, provided sufficient restraint to prevent the crack from progressing.

To quantify the plastic shrinkage cracking of rubber containing mortars, the width of the cracks was measured at 1 h, 2 h, and 3 h in the drying chamber. The results are summarized in Table 6. After 3 hours, the mortar specimen (control) developed a crack having an average width of about 0.9 mm, while the average crack width for the specimen with 5% fibrous rubber was about 0.4 mm. It was found that the onset of cracking was delayed by the addition of fibrous rubber: the mortar without fibers cracked within 30 min., while the specimens with 5% and FR 4.75 fibrous rubber of fibrous rubber cracked after 1 hour. The crack length, the crack width and the time of failure of the rubber containing mortar were dependent on the contents of fibrous rubber in the mortar.

Table 6: Plastic shrinkage cracking results

Fibers added to the mortar	Amount (% by mass of cement	Number of Cracks	Crack length (mm)			Average crack width (mm)			Time of first crack
			1h	2h	3h	1h	2h	3h	(min.)
None	0	1	158	212	246	0.3	0.6	0.9	25
Polypropylene	1	0	0	0	0	0	0	0	No cracks
FR 4.75	5	2	174	212	212	0.2	0.4	0.6	30
	10	2	156	203	203	0.2	0.2	0.4	60
	15	4	103	142	178	0.2	0.3	0.4	60
FR 2.36	15	4	163	181	203	0.2	0.3	0.3	35
GR 2	15	3	107	204	219	0.2	0.2	0.4	45

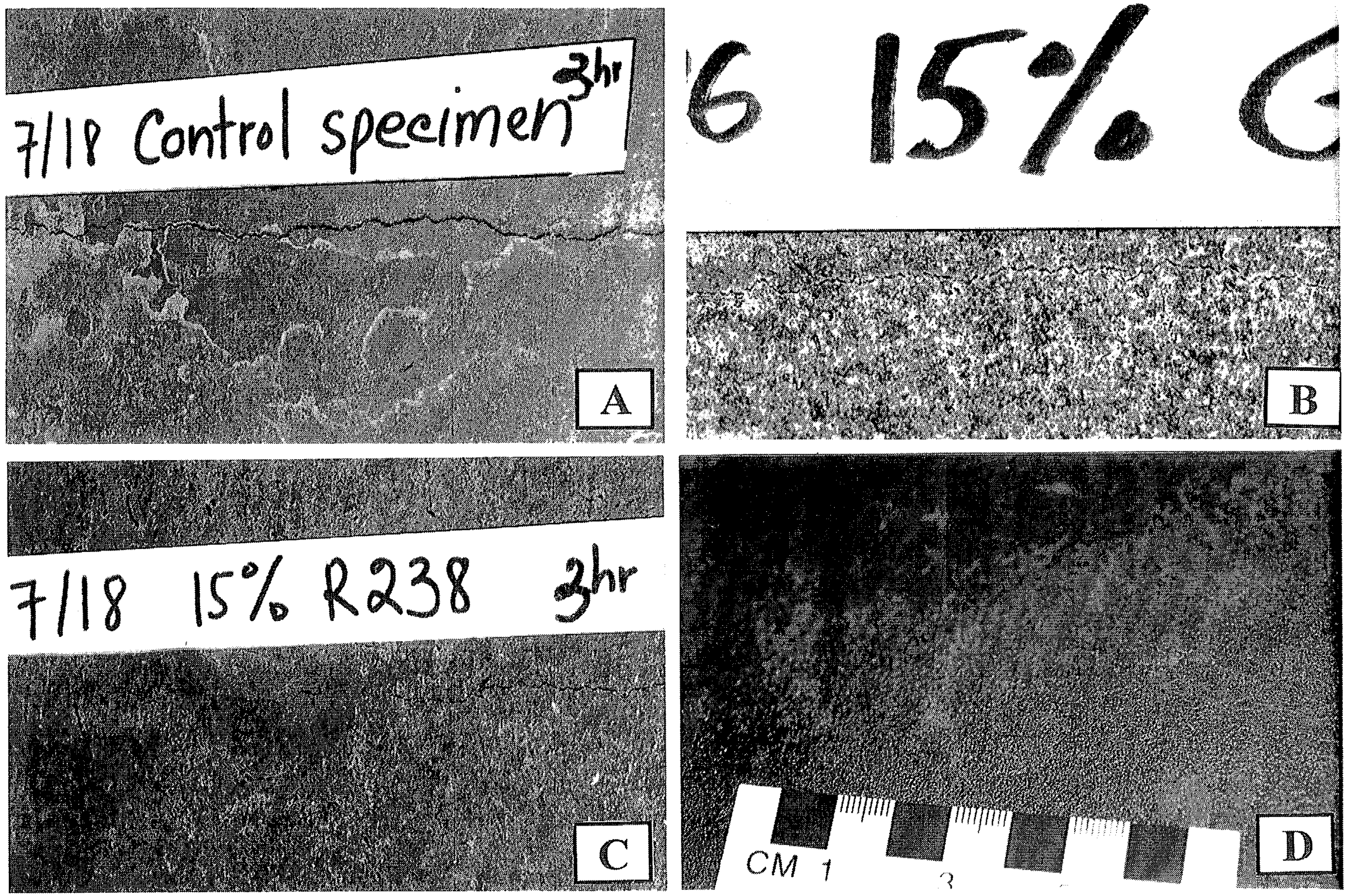

Figure 10: Picture of specimen surfaces after testing for plastic shrinkage cracking (a) mortar, (b) 15% granular rubber-mortar, (c) 15% fibrous rubber-mortar (d) 1% polypropylene fiber-mortar.

3.4. *Workability*

Table 7 summarizes the results of workability measurements. The control mixture and the mixture with 10 % fibrous rubber had similar VeBe times, while the mixture with 1 % fibrous rubber had a lower VeBe time. The VeBe time for 1 percent polypropylene fibers was much larger (241 sec.). It is believed that the effects of the polypropylene fibers in preventing the free flow of the mixture are attributable to their greater number and high aspect ratio.

Table 7: Workability measurements

Material Added to the mortar	VeBe time [s]		
	0 %	1 %	10%
	by mass of cement		
Polypropylene	55 ± 1	241 ± 8	
GR2	55 ± 1	40 ± 2	58 ± 3
FR 2.36	55 ± 1	36 ± 1	50 ± 4
FR 4.75	55 ± 1	26 ± 1	44 ± 3

4. CONCLUSIONS AND RECOMMENDATIONS

A preliminary study was performed to investigate the effects of adding rubber in either granular or fibrous form to mortar. For comparison, some tests were done with mortar containing polypropylene fibers. The following conclusions were drawn from this study :

- The compressive and flexural strengths of the mortar decreased with increasing contents of rubber granules or fibers. A smaller reduction in mortar strength was observed with fibrous rubber than with the granular rubber.
- In fractured specimens of mortar containing granular rubber, the rubber particles pulled out from the matrix. This was taken as evidence of weak interfacial bonding between the rubber and matrix. The fractured specimens of mortar containing fibrous rubber exhibited bridging of cracks by the fibrous particles. Even though, the matrix was completely fractured under flexural load, the fibrous rubber particles held the specimen together.
- The severity of the plastic shrinkage cracking was reduced by the addition of fibrous rubber compared with the control mortar. The content of fibrous rubber in the mortar affected the onset time of cracking, the crack length, and the crack width. The particles of fibrous rubber bridged the cracks and provided restraint to crack widening.
- The mortar containing fibrous rubber showed workability comparable to that of mortar without fibers, while the mortar containing polypropylene fibers showed poor workability.

It is proposed to conduct further tests to provide more information about the best size and content of particles of fibrous rubber for preventing plastic shrinkage cracking without causing large reductions in the compressive and flexural strengths of the mortar. The proposed study will be extended to concrete specimens to examine the effects of fibrous rubber on the overall properties and the workability of concrete.

5. ACKNOWLEDGEMENTS

The authors thank the Polymer Division and the Building Materials Division of NIST, IBM, and the Department of Chemistry at Howard University for providing support to Ms. H. Huynh. The authors would like to thank G. Frohnsdorff and D. Hunston from NIST for many helpful discussions during the course of this investigation. We would like to acknowledge especially Dr. N. Carino who provided the essential statistical analysis of the results. Special thanks are due to the Rouse Rubber Company and to the Baker Industries Inc. for providing rubber samples, and to the W. R. Grace Company for providing polypropylene fibers.

6. REFERENCES

(1) Anonymous, "New Directions", Advanced Materials and Processes, 135(1), 21(1989).

(2) J. Paul, "Rubber Reclaiming", Encyclopedia of Polymer Science and Engineering, 14, 787(1985).

(3) H. B. Takallou, and M. B. Takallou, "Recycling Tires in Rubber Asphalt Paving Yield Costs Disposal Benefits", Elastomeric, 123(7), 19(1991).

(4) W. O'Keefe, "Stone, Clay and Glass : Fuel Price Shift Puts Fully Researched Tire Burning on Hold at Cement Plant", Power, 128(10), 115(1984).

(5) B. Lee, "Research in Progress in Developing Tire-Concrete at the Center for Advanced Construction Materials", ACI Spring Convention in Salt Lake City, Utah, 1995.

(6) Anonymous, "Recycled Tires Down the Road", Biocycle, 34, 9(1993).

(7) H. Goldstein, "Not Your Father's Concrete", Civil Engineering, 65(5), 60(1995).

(8) N. N. Eldin, "Use of Scrap Tires in Road Construction", Journal of Construction Engineering and Management, 118(3), 561(1992).

(9) N. N. Eldin and A. B. Senouci, "Observation of Rubberized Concrete Behavior", Cement Concrete and Aggregates, 15(1), 74(1993).

(10) Workshop on National Cooperation Strategies for Reuse of Waste Rubber Tires in Infrastructure, NIST, Gaithersburg, MD, Oct. 14, 1994, Unpublished Report, Compiled by D. Raghavan, G. M. Sabnis, and S. Ahmad.

(11) B. I. Lee, L. Burnett, T. Miller, B. Postage and J. Cuneo, "Tire Rubber/Cement Matrix Composite", Journal of Materials Science Letter, 12(13), 967(1993).

(12) D. Raghavan, K. Tratt, and R. P. Wool, "Recycled Rubber in Cement Composite", MRS Symposium Proceedings, 344, 177(1994).

(13) D. Raghavan, K. Tratt, and R. P. Wool, " Interfacial Bonding of Recycled Rubber Cement Composites", Processing of Advanced Materials, 1995, in press.

(14) F. Shutov and S. Volfson, " New Principles of Plastic Waste Recycling : Solid State Shear Extrusion", Polymer Materials Science and Engineering, 67, 404(1992).

(15) P. Balaguru, R. Narahari, and M. Patel, "Flexural Toughness of Steel Reinforced Concrete", ACI Materials Journal, 89(6), 541(1992).

(16) P. Soroushian, A. Khan, and J-W Hsu, "Mechanical Properties of Concrete Materials Reinforced With Polypropylene or Polyethylene Fibers", ACI Materials Journal, 89(6), 535(1992).

(17) A. Nanni, D. A. Ludwig and M. T. McGillis, "Plastic Shrinkage Cracking of Restrained FRC", Transportation Research Record, 1382, 69(1993).

(18) Standard Test Method for Compressive Strength of Hydraulic Cement Mortars, ASTM Designation C109, 1994 Annual Book of ASTM Standards, Vol. 04.01

(19) Standard Specification for Standard Sand, ASTM Designation C778, 1994 Annual Book of ASTM Standards, Vol. 04.01.

(20) Standard Specification for Wire-Cloth Sieves for Testing Purposes, ASTM Designation E11 , 1987 Annual Book of ASTM Standards, Vol. 14.02.

(21) Standard Test Method for Compressive Strength of Cylindrical Concrete Specimen, ASTM Designation C39, 1993 Annual Book of ASTM Standards, Vol. 04.02.

(22) Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Third Point Loading), ASTM Designation C78, 1993 Annual Book of ASTM Standards, Vol. 04.02.

(23) M. S. Abdel-Azim, " Durability of Palm-Tree Frond Fiber Reinforcement", Concrete International, 17, 27(1995).

(24) G. H. Tattersall, "Workability and Quality Control of Concrete", pp. 19-21, 1st edition, 1991.